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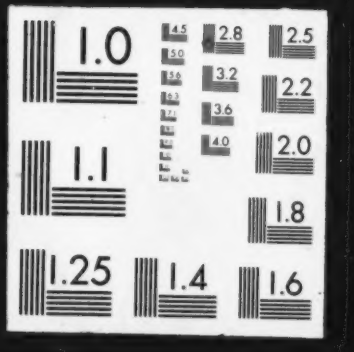

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Nitric Oxide Reduction in Kilns and Heaters by Fuel/Air Staging

KVB, Inc., Irvine, CA

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NITRIC OXIDE REDUCTION IN KILNS AND HEATERS BY FUEL/AIR STAGING

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Minneapolis, MN

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16. ABSTRACT: The paper gives results of studies of the applicability and effectiveness of fuel/air staging (variously called In-furnace NOx Reduction, reburning, or biased firing) in controlling nitrogen oxide (NOx) emissions from refinery process heaters and cement kilns. The studies were conducted in three laboratory subscale furnaces and during a short-term test on a full-scale cement kiln. One furnace, firing natural gas at 38 kW, was designed to simulate operating conditions of a petroleum process heater. The second furnace, firing natural gas and coal at 50 kW, was designed to simulate the operating conditions of a dry process precalcining cement kiln. Test results showed that 50-70% reductions in stack NOx emissions can be readily achieved by fuel staging under the conventional mode (conventional air staging plus fuel injection between the main burner and the staging air injection point), and much similarity between conventional fuel staging (reburning) and air staging was observed. Fuel staging was investigated further in a third gas-fired 58.7 kW laboratory test furnace to examine biased firing as either a retrofit or a new burner concept. Test results showed that 80-85% reductions in stack NOx emissions can be achieved by biased firing and the optimum fuel split is around 50%. It was also found that reductions in NOx were slightly more effective with a retrofit lance approach.

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Nitrogen Oxides	Stationary Sources	07B 21D
Kilns	Fuel/Air Staging	13A
Cements	Cement Kilns	11B, 13C
Heating Equipment		
Refineries		13I
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ABSTRACT

The applicability and effectiveness of fuel/air staging (variously called In-Furnace NO_x Reduction, reburning, or biased firing) in controlling nitrogen oxides (NO_x) emissions from refinery process heaters and cement kilns were studied in three laboratory subscale furnaces and during a short-term test on a full scale cement kiln. One furnace, firing natural gas at 38 kW (130,000 Btu/hr), was designed to simulate operating conditions of a petroleum process heater. The second furnace, firing natural gas and coal at 50 kW (170,000 Btu/hr), was designed to simulate the operating conditions of a dry process precalcining cement kiln. Test results showed that 50 to 70 percent reductions in stack NO_x emissions can be readily achieved by fuel staging under the "conventional" mode (conventional air staging plus fuel injection between the main burner and the staging air injection point), and much similarity between conventional fuel staging (reburning) and air staging was observed. Fuel staging was investigated further in a third gas-fired 58.7 kW (200,000 Btu/hr) laboratory test furnace to examine biased firing as either a retrofit or a new burner concept. Test results showed that 80 to 85 percent reductions in stack NO_x emissions can be achieved by biased firing and the optimum fuel split is around 50 percent. It was also found that reductions in NO_x were slightly more effective with a retrofit lance approach. Short-term tests were conducted on a full scale coal-fired cement kiln to evaluate fuel staging by firing the coal in two streams: one with normally pulverized coal and a second with lump coal (3-10 mm). NO_x was reduced to 450 ppm from 800 ppm, about 40 percent reduction. Process variability, however, produces a wide uncertainty band on the data.

BACKGROUND AND OBJECTIVES

In the past, significant reductions of NO_x emissions from combustion sources have been demonstrated by the application of the conventional two-stage combustion (air staging) process which utilizes the injection of air downstream of the main combustion zone fired under fuel-rich conditions.[1-5] A process similar to conventional staging but which may have potentially greater effects on NO_x reduction is the In-Furnace NO_x Reduction Process (IFNR) which utilizes the injection of both air and fuel in the second stage. This process is also known as reburning or fuel staging. The first practical system employing a form of NO_x reduction by reburning was commercialized by the John Zink Company[6] in 1969. The results obtained by Japanese researchers showed that NO_x reductions on the order of 50 percent over and above what has already been achieved by other means can be accomplished in full-size furnaces fired with gas, oil, or pulverized coal.[7-10]

Although most of the research works cited above have been performed with emphasis on boiler applications, the process of In-Furnace NO_x Reduction is quite fundamental in nature and can be effective in reducing NO_x emissions when applied to a wide spectrum of stationary combustion sources. With this in mind, KVB has conducted a subscale research program under the sponsorship of the United States Environmental Protection Agency (EPA) with the objective of investigating the application of the In-Furnace NO_x Reduction process in industrial combustion equipment such as refinery process heaters and cement kilns.

POSSIBLE FUEL/AIR STAGING ARRANGEMENTS

With the additional flexibility gained through the separate injection of reburn fuel, there are many possible firing arrangements that may come under the heading of "In-Furnace NO_x Reduction" (IFNR). A sample of these is shown in Figure 1. Included are the firing arrangements for (a) air staging, (b) conventional IFNR, (c) combined air staging and IFNR, (d) all fuel-lean IFNR, (e) biased firing, and (f) advanced biased firing. The third arrangement (c) is one that connects the firing arrangements of air staging and conventional IFNR in series. According to the Japanese researchers[8,9] 50 percent reduction of NO_x can be achieved at any initial NO_x level; therefore, this firing arrangement should offer the potential of great reductions in NO_x emissions. Firing arrangement (d), all-fuel-lean IFNR, differs from conventional IFNR in that the reburn zone is maintained fuel-lean. With this, nowhere in the furnace are the combustion products fuel-rich; therefore, the potential for corrosion would be the lowest.

Firing arrangement (e), biased firing, consists of a minimum of two rows of burners with the lower row firing fuel-rich and the upper row firing fuel-lean. It differs from the other firing arrangements in that there is no individual injection of fuel or air and all fuel and combustion air are fired from burners at various stoichiometric ratios. Firing arrangement (f), advanced biased firing, is an extension of biased firing with a certain amount of air split off as staging air.

All of these firing configurations were evaluated in the test programs reported here.

TEST FACILITIES

Three laboratory tests were conducted in three different tubular refractory-lined furnaces varying in diameter from 12.7 cm (5 inches) to 35.6 cm (14 inches) and in length from 2.13 m (7 feet) to 3.66 m (12 feet). Combustion air was preheated to 260°C (500°F). Air and fuel injection points were provided along the furnaces for staging at variable residence times.

A fourth test was conducted in a full-scale production cement kiln 4.1 m (13.5 feet) diameter by 149 m (490 feet) long, fired with pulverized coal at 70.3 MW (240 million Btu/hr) producing 41 metric tons of cement

clinker/hr. Gaseous emissions of NO, CO, CO_2, SO_2, and O_2 were measured with continuous gas analyzers.

LABORATORY SCALE PROCESS HEATER REBURNING

Tests of all the firing configurations, except configuration (e), biased firing, shown in Figure 1 were conducted in a tubular furnace 20.3 cm (8 inches) in diameter by 2.13 m (7 feet) long. The furnace was fired with natural gas at a heat input of 38 kW (130,000 Btu/hr).

The results of these tests have been previously reported[11]; the most pertinent results are summarized in Figure 2, comparing air staging (Figure 1a), In-Furnace NO_x Reduction (Figure 1b), and advanced biased firing (Figure 1f). The major conclusion was that air staging and IFNR both produced nearly identical NO_x reductions on the order of 60 to 70 percent. Advanced biased firing, on the other hand, produced significantly greater NO_x reduction, up to 90 percent, when the fuel staging split was 50/50 and the first stage was operated at 50 percent stoichiometry.

LABORATORY SCALE PROCESS HEATER BIASED FIRING

Based on the promising results with advanced biased firing, a second test program was conducted to expand the range of test variables and to examine a different method of fuel injection that would be more easily adapted to existing burner designs. The firing configuration corresponds to (e) in Figure 1, biased firing. Advanced biased firing differs from biased firing in having a separate air injection stage downstream of the second-stage fuel/air injection. Limited tests comparing these two configurations indicated that the extra air stage with advanced biased firing did not produce significantly lower NO_x to warrant the additional complexity. Therefore, only biased firing was investigated in the second test program.

The process of biased firing divides the combustion furnace into two distinct regions. The main burner is fired under substoichiometric conditions thus forming a fuel-rich region. This region is surrounded by a fuel lean region where the remaining portion of fuel and combustion air is introduced. Farther downstream, the mixing of the fuel-rich and fuel-lean combustion product streams completes the combustion process.

The laboratory combustion apparatus was designed to simulate a vertically fired cylindrical process heater. It had an internal diameter of 35.6 cm (14 inches) and was 2.13 m (9 feet) long. The nominal firing rate was 58.7 kW (200,000 Btu/hr). A schematic drawing of the gas fuel burner arrangement is shown in Figure 3. The biased-firing lance system consisted of replaceable lances of various diameters with the capability to provide various degrees of swirl by use of swirl vanes. Biased-fired fuel and air could be introduced at any location along the length of the furnace. Preheated air was introduced at the bottom of the burner and flowed upward, parallel to the axis of the cylindrical burner. For proper flame stabilization, a bluff body cen-

tered around the burner axis was used to produce airflow at a high velocity through an annulus to create turbulence at the point of fuel injection.

The degree of fuel split had the most significant influence on NO_x emissions. Under the biased firing arrangement, the amount of NO_x decreased as an increasing amount of fuel was burned in the biased-fired fuel-lean zone (Figure 4). These reductions, however, were not significantly improved beyond a fuel split of 50 percent. In addition, beyond a fuel split of 50 percent, the emission of CO may become a problem due to potential flame instability. A maximum of 90 percent reduction of NO_x was achieved with 50 percent fuel split and a first stage stoichiometry of 30 percent.

The capability to reduce NO_x through biased firing was found to be relatively insensitive to overall furnace stoichiometry, burner separation, air swirl, and firing rate. For all tests, the burner was operated without biased firing to establish baseline emissions. The burner was adjusted to vary baseline NO_x emissions from 75 to 145 ppm, and these adjustments did not significantly affect the percent reduction obtained when biased firing was subsequently applied.

Visual observations indicated that biased firing lengthened the main burner flame. Flame length was determined as the centerline distance above the main burner at which CO concentration was 1 percent. A fuel split of 50 percent increased the flame length by a factor of approximately four.

LABORATORY SUBSCALE CEMENT KILN REBURNING

The objective of this test series was to investigate NO_x reduction methods for cement kilns which are designed with a precalcining process. In non-precalcining kiln systems, all of the fuel is fired through a single burner in the kiln. In precalcining systems, the fuel is divided -- one-third to one-half is fired in the kiln, and the balance is fired in the precalciner. This division of the firing, while done for process purposes, is a form of fuel staging, and research by kiln manufacturers[12], conducted with oil fuel, indicated that the precalcining systems had lower NO_x emissions compared with non-precalcining systems. Several precalcining kiln systems were built in the U.S. in the late 1970s and early 1980s with NO_x emission limit commitments based on the oil-fired research data but were designed to fire coal. Considerable difficulty was experienced in complying with NO_x limits attributed to the effect of fuel-bound nitrogen in the coal, which had apparently not been adequately accounted for in assessing the emission limits. The higher NO_x emissions with coal have been confirmed by kiln manufacturers[13].

Although these precalcining systems are already operating with fuel staging, the objective of the test reported here was to investigate the benefit from applying additional staging within the precalciner section itself.

The subscale laboratory furnace used is shown schematically in Figure 5. It was a refractory-lined tubular furnace with an internal diameter of

12.7 cm (5 inches) and a length of 3.06 m (12 feet). It consisted of a kiln section and a precalciner section. The precalciner section was further divided into three sections: the first precalciner (PC) stage, the reburn stage, and a second PC stage. It should be noted that no cement materials were introduced, and there was no rotation of any parts as occurs in an actual kiln. The objective was to simulate only the main combustion zone conditions, not the flame/material interaction which, in fact, may have a significant effect on NO_x emissions.

Initial tests involved firing only the kiln section with coal at the full heat input of 50 kW (170,000 Btu/hr). The coal was a Montana Rosebud subbituminous coal with 0.84 percent fuel nitrogen and was ground to 75 percent through 200 mesh. NO_x emissions of 430 ng/J (1 lb/10^6 Btu, about 720 ppm) were measured and were used as one form of baseline for subsequent fuel staging tests.

A second baseline condition was established by firing the kiln section with natural gas and the precalciner section with coal and supplying combustion air at each point in sufficient quantity to burn the fuel at that point. The natural gas was spiked with ammonia to bring NO_x up to levels observed in the initial baseline test. The kiln-to-precalciner heat input ratio (natural gas to coal) was 47:53, and the total combined heat input of both fuels was equal to that of the initial baseline test. For this second baseline test, NO_x emissions of 241 ng/J were measured, a significant reduction from the initial baseline, supporting the indications of lower NO_x emissions for precalcining systems.

The next series of tests involved staging the air in the precalciner section. Test results are shown in Figure 6. As the precalciner first-stage stoichiometry (SR_1) was decreased, stack NO_x was reduced proportionally. For an SR_1 of 70 percent, stack NO_x was reduced to 129 ng/J, a reduction of 70 percent from the initial single-stage baseline and 46 percent from the second two-stage baseline.

The test results obtained with the reburning mode are shown in Figure 7. The two data curves for fuel-rich reburn zone stoichiometries (SR_2 = 0.75 and 0.84) showed that, as more fuel was being reburned, stack NO_x increased from the respective levels that were observed for air staging (Figure 6).

The data in Figure 7 for SR_2 = 1.0 and 1.2 show that, when the reburn stage was fuel-lean, reburning produced better results in terms of NO_x reduction than air staging at the same lean stoichiometries. This is consistent with the subscale process heater results. The reductions, however, were not great.

The results of the subscale cement kiln furnace tests appeared to indicate that, in terms of NO_x emissions reduction, the performance of precalciner section reburning is inferior to that of air staging. These results

were consistent with those of the subscale process heater tests reported earlier.

It should be noted that the effects of staged combustion in the precalciner section on the overall cement making process were beyond the scope of these tests, and should be studied thoroughly before any full scale combustion modification is to be considered.

LUMP COAL CEMENT KILN FUEL STAGING

A cement plant at which KVB previously conducted nitrogen injection tests in the primary air stream[14] had an internal research program to evaluate the firing of two coal sizes simultaneously as a form of fuel staging. In addition to normal coal, about 10 to 30 percent of the heat input was provided by finely divided, but unground, coal sized in 0.3 cm (1/8-inch) to 0.5 cm (1/5-inch) lumps. The lump coal was injected parallel to the normal coal through a separate pipe with the objective of creating a secondary combustion zone downstream of the normal coal burning zone. Although the tests were internal company research, the company agreed to have KVB participate in the test program to obtain the benefit of the data for EPA. The objective of KVB's participation was to observe the tests conducted by the company, obtain emission data, and report the results. The test facility (Figure 8) for these combustion modification tests was a long dry non-precalcining rotary cement kiln 4.1 m (13.5 feet) inside diameter and 149 m (490 feet) long. The production rate was 41 metric tons of clinker per hour. The thermal input rate was approximately 70.3 MW (240 x 10^6 Btu/hr) of Southern Utah bituminous coal.

During lump coal testing, KVB monitored stack gas emissions and operational data from the control room. The on-line continuous emissions monitor provided information on oxygen (O_2, %), carbon monoxide (CO, ppmv), nitric oxide (NO, ppmv), carbon dioxide (CO_2, %), and sulfur dioxide (SO_2, %). All emissions were reported on a dry basis. Approximately 15 hours of lump coal testing was performed. Prior to the start of lump coal testing, approximately 15 hours of as-found data were collected. Figure 9 shows the time trace of NO_x and CO, corrected to 3 percent O_2, along with the total coal flowrate in tons per hour. The NO_x ranged between 800 and 1300 ppm, and all the CO data were less than 150 ppm. The coal firing rate was approximately 9.2 tons per hour throughout the as-found testing period. The kiln operation was briefly interrupted on a few occasions due to a plugged coal pipe and later due to the loss of the coal weigh feeder. The lump coal testing was discontinued when the kiln ID fan went out of service. The NO_x did decrease during the last 4 hours of the lump coal testing from approximately 800 ppm to approximately 450 ppm at 3 percent O_2. CO spikes of over 400 ppm (maximum on 0-400 range) also occurred during the course of the testing. The total coal flowrate was approximately 1 ton per hour less during the last 7 hours of testing than compared to the as-found pulverized coal rate.

The coefficient of variation for the baseline NO_x emissions ranged from a low of 7.4 percent to a high of 18.8 percent. Based on previous emissions data collection, the kiln was operating in a steady mode. The steady operating conditions were favorable for establishing a reference baseline to judge the extent of NO_x reduction with lump coal testing. The coefficient of variation for NO_x during the lump coal test series ranged from a low of 7.3 percent to a high of 38.2 percent. Thus, the kiln operation was not as steady during the lump coal test series. The reason(s) for the less steady operation may or may not be associated with the lump coal. Although the extent of reduction is significant, the evaluation of the NO_x reduction potential with lump coal is very difficult because of fluctuating kiln operating conditions. The kiln burning zone temperature change during the lump coal testing may be due to a change in kiln feed composition, kiln hood pressure, or any one or a combination of other changes.

Operational data from the control room were collected approximately every 2 hours. No clinker samples or kiln feed samples were collected by KVB during the test program. However, the plant did collect clinker samples during the testing, and reported that clinker quality was not adversely affected during the lump coal testing.

SUMMARY AND CONCLUSIONS

Based on the results obtained during testing of the In-Furnace NO_x Reduction (IFNR) process in three subscale laboratory furnaces operated at conditions of petroleum process heaters and cement kilns, the following conclusions were drawn:

- The process of In-Furnace NO_x Reduction can be carried out under many fuel/air staging arrangements. For different applications, the optimum firing arrangements may very well be different. Therefore, the relative effectiveness of each firing arrangement must be considered before optimum conditions can be reached for a particular application.

- Stack NO_x reductions of over 50 percent can be achieved with conventional IFNR. However, results from both subscale process heater and cement kiln tests have shown that the NO_x reducing capability of conventional IFNR was only as great as that of air staging.

- Although conventional IFNR has been shown to be comparable in reducing NO_x when compared to air staging, it does offer one potential benefit. It reduces the length of furnace which is exposed to fuel-rich conditions and, therefore, the possibility of corrosive environments.

- Of the fuel/air staging arrangements tested, the most promising fuel/air staging arrangement for refinery process heater application is biased firing. Stack NO_x reductions of greater than 90 percent from the unstaged baseline have been achieved.

- Under the biased firing arrangement, NO_x decreased with increasing amounts of fuel being burned at the reburn zone. The gains were, however, not significant beyond a reburn fuel split of 50/50.

- Increasing the spatial separation of biased firing burners and the main burner only decreased NO_x moderately.

- The results of laboratory tests simulating precalciner cement kiln conditions show significant NO_x reductions with air staging which was superior to reburning in reducing NO_x. Further work is necessary, including process material interaction, before application to actual kilns can be considered.

Based on the results obtained during short-term testing of pulverized and lump coal in a full-scale long dry non-precalcining cement kiln, the following conclusions were drawn:

- NO_x reductions of up to 40 percent from the baseline test conditions offer promise for reducing cement kiln NO_x.

- Further evaluation of process variability is necessary over longer test periods.

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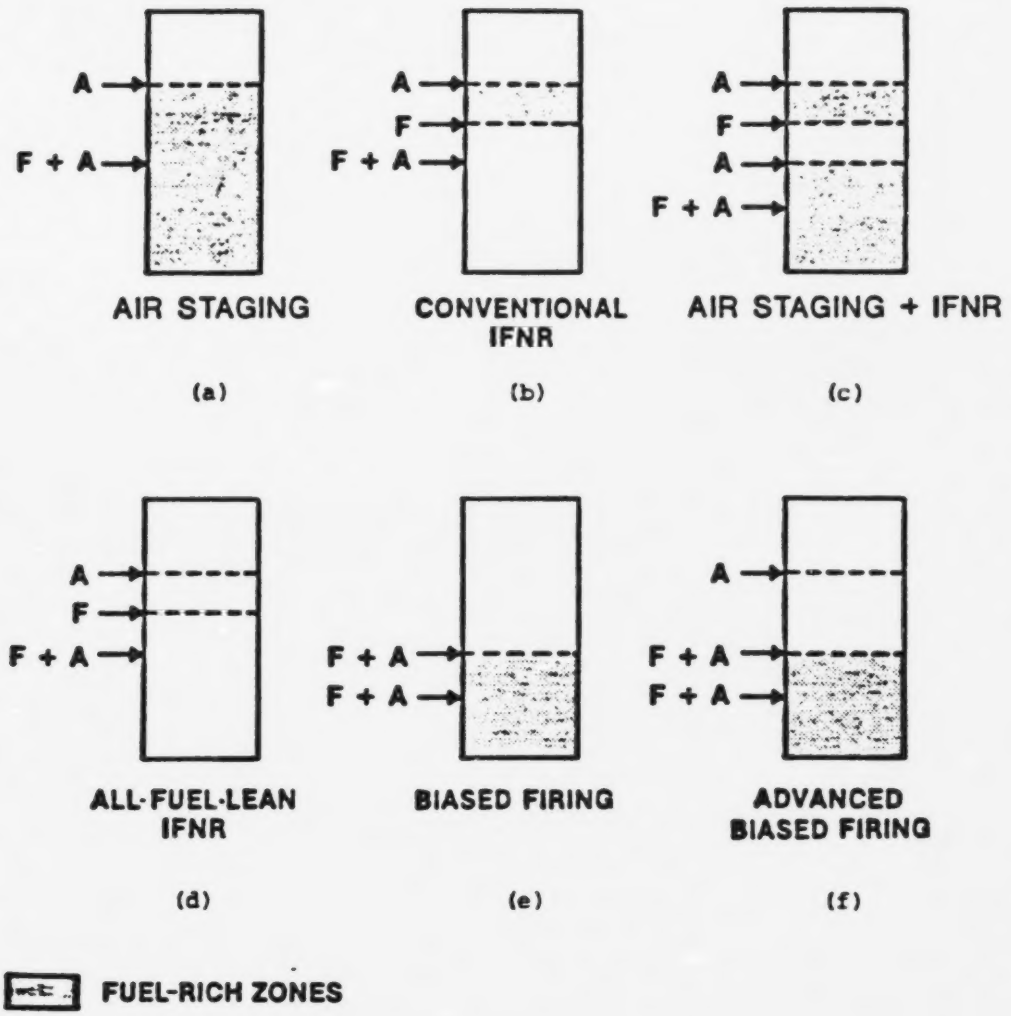

Figure 1. Examples of possible fuel/air staging arrangements.

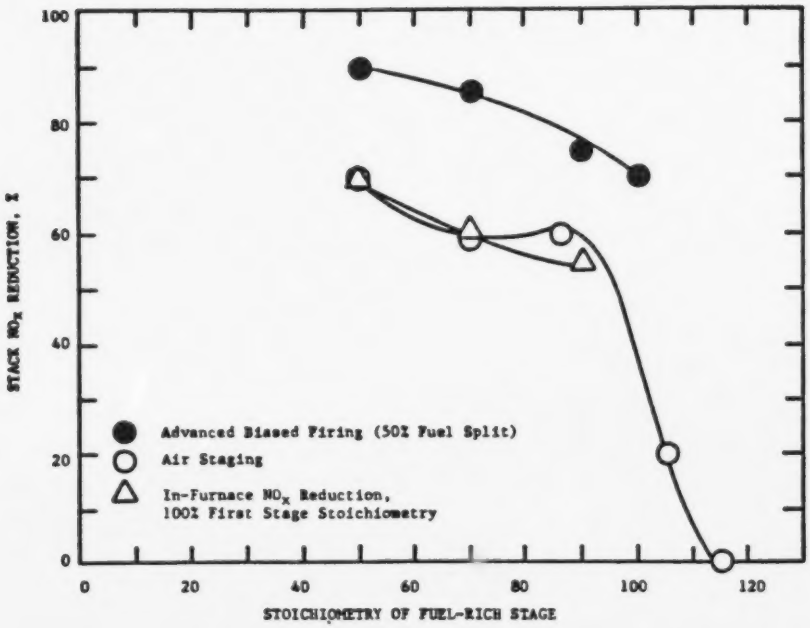

Figure 2. Comparison between conventional IFNR, air staging, and advanced biased firing potential for NO_x reduction.

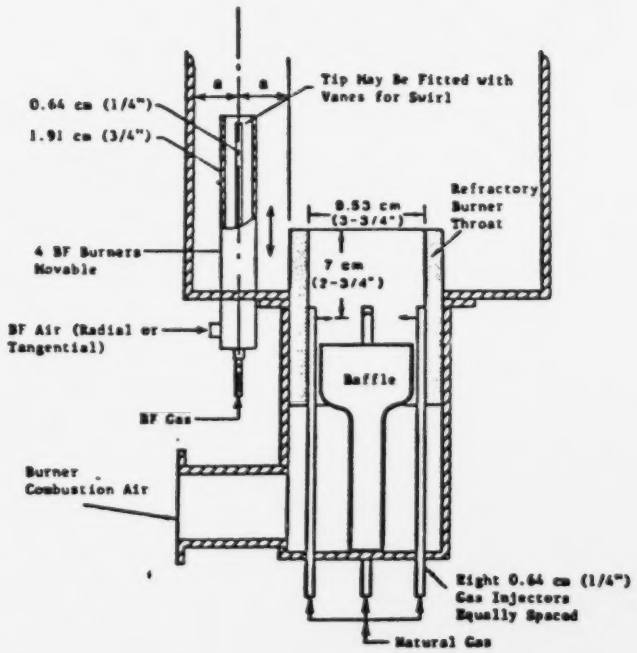

Figure 3. Gas burner arrangement.

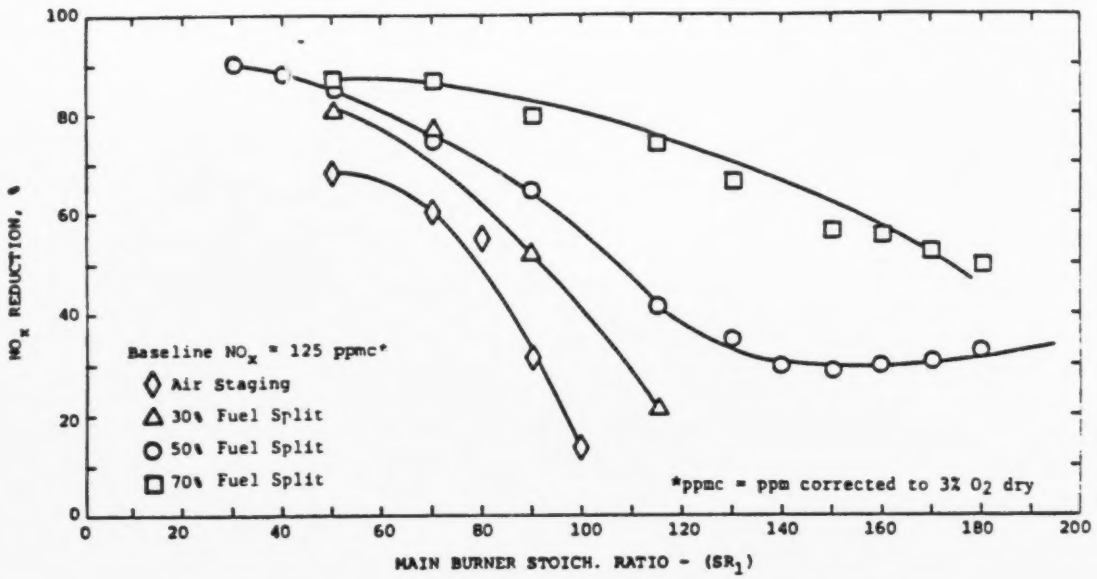

Figure 4. Effect of fuel split [Furnace Load = 58.7 kW (200,000 Btu/hr), Excess O_2 = 3%, Lance Location = 30.5 cm (12 inches) above Main Burner]

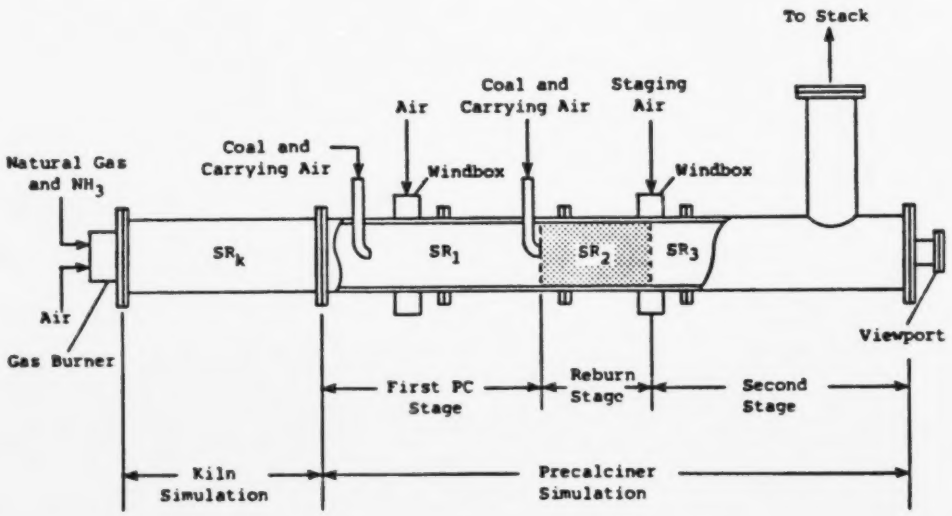

Figure 5. Schematic drawing of the subscale cement kiln test furnace.

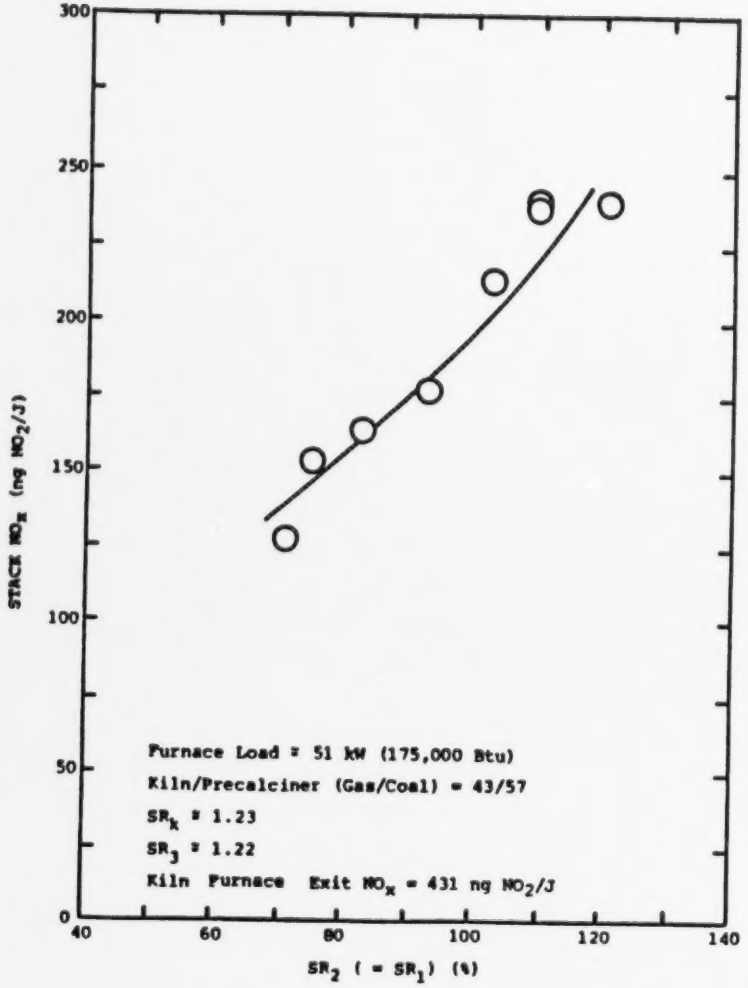
STACK NO_x (ng NO_2/J)
SR_2 (= SR_1) (%)
Furnace Load = 51 kW (175,000 Btu)
Kiln/Precalciner (Gas/Coal) = 43/57
SR_k = 1.23
SR_3 = 1.22
Kiln Furnace Exit NO_x = 431 ng NO_2/J

Figure 6. Results of precalciner air staging.

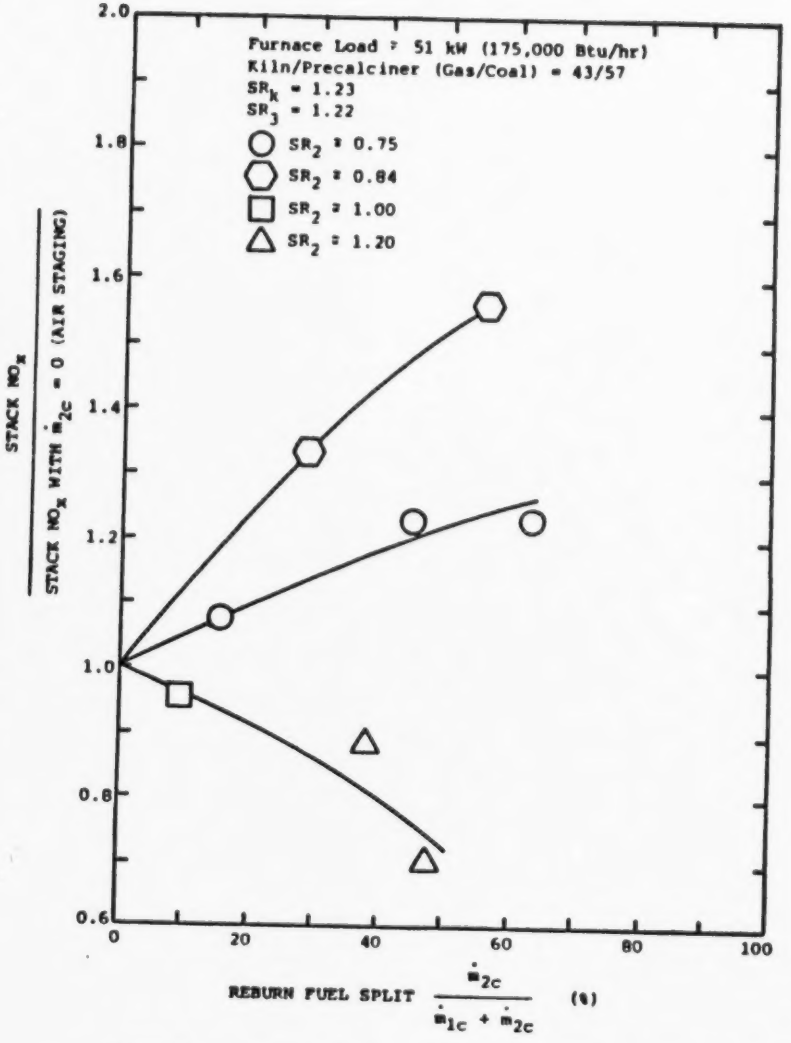
Furnace Load = 51 kW (175,000 Btu/hr)
Kiln/Precalciner (Gas/Coal) = 43/57
SR_k = 1.23
SR_3 = 1.22
SR_2 = 0.75
SR_2 = 0.84
SR_2 = 1.00
SR_2 = 1.20
STACK NO_x / STACK NO_x WITH $\dot{m}_{2c}$ = 0 (AIR STAGING)
REBURN FUEL SPLIT $\frac{\dot{m}_{2c}}{\dot{m}_{1c} + \dot{m}_{2c}}$ (%)

Figure 7. Results of precalciner reburning ($\dot{m}_{1c}$ and $\dot{m}_{2c}$ are injection rates of pulverized coal at the first and the second injection points).

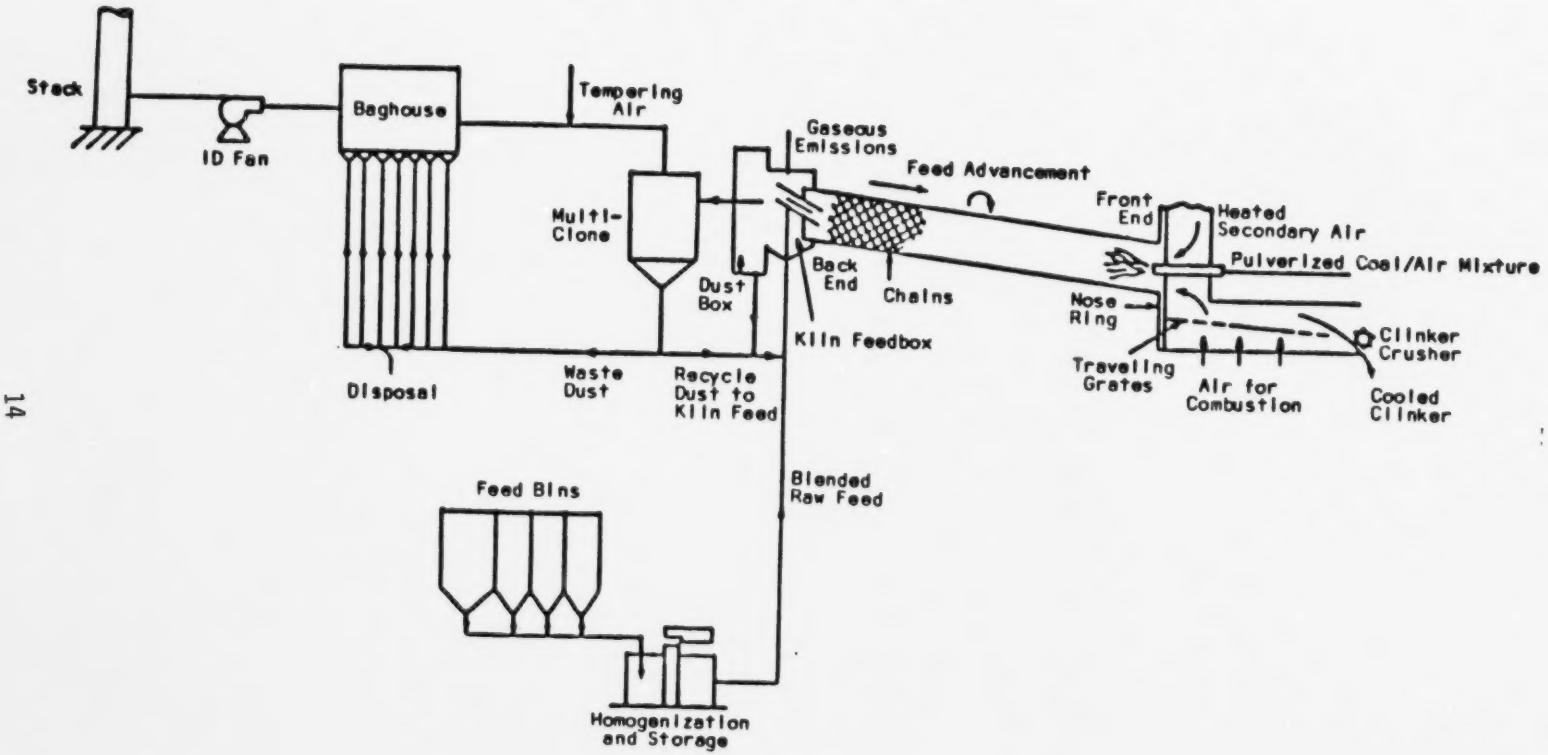

Figure 8. Schematic of dry process cement kiln system.

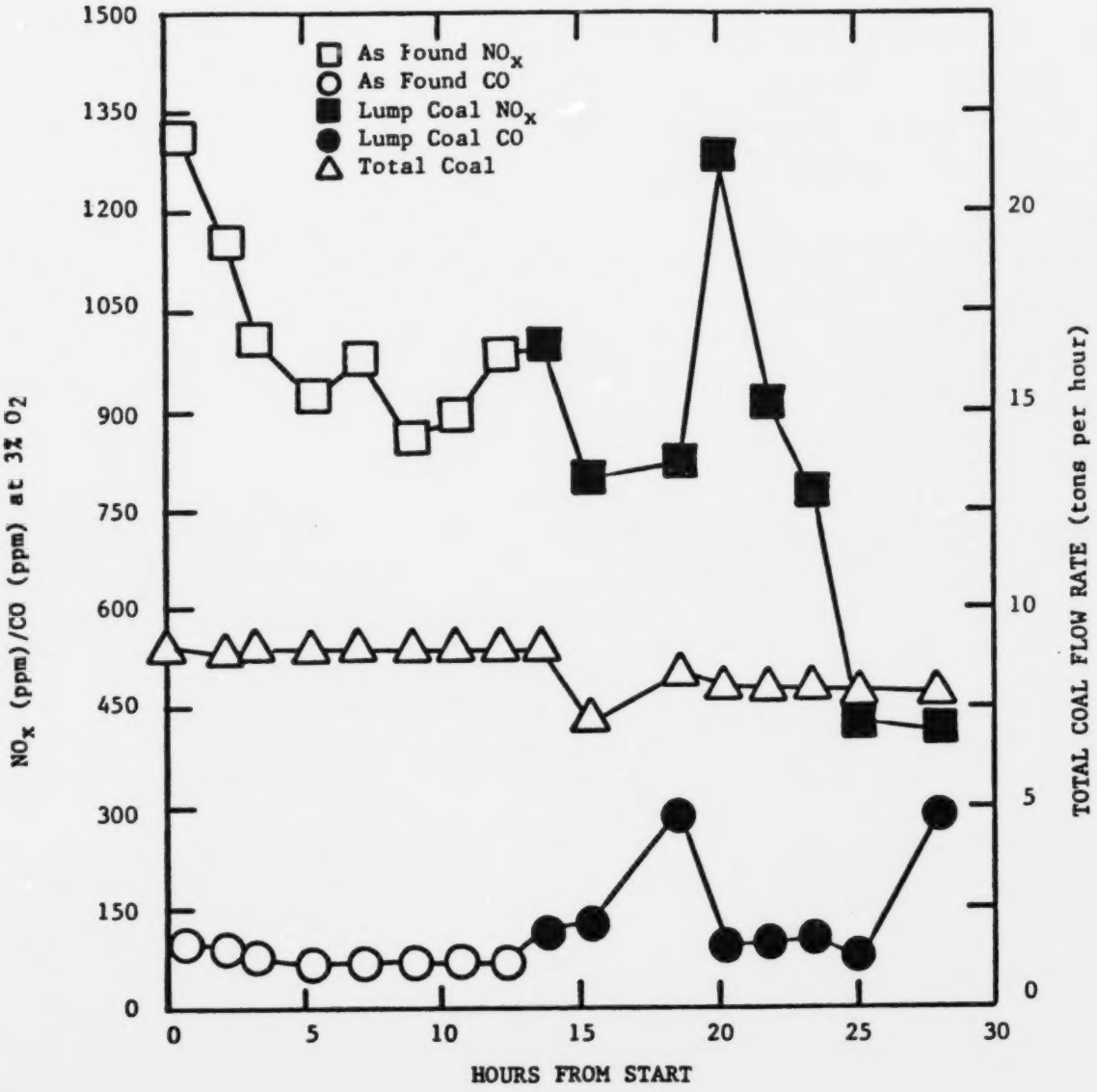

Figure 9. As found and lump coal test results for full scale cement kiln.